HIGH-TEMPERATURE MEMS BASED SEISMOMETER

HOTTECH-2 F2F MEETING AUG 8-9

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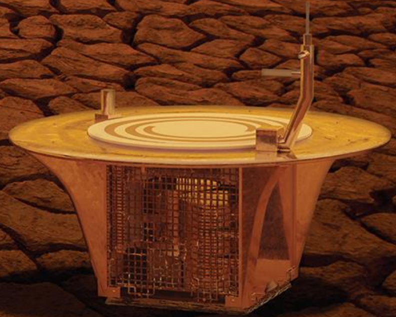
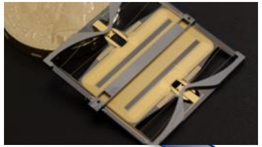
NASA GLENN RESEARCH CENTER

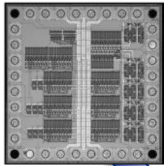
Outline

1. General Overview
2. Science Motivation
3. Science Team Progress / Contributions
4. Technical Plan / Status
5. Partnering Opportunities



High-Temperature MEMS based Seismometer





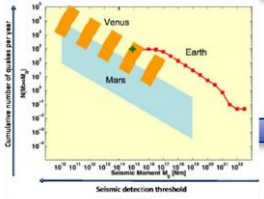
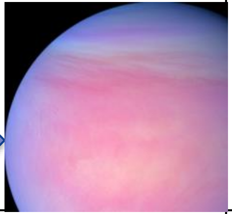


Fig. 1. Estimated Venus Seismic Activity [Error!



Core Team Member(s) / Institution(s)

T. Kremic / PI — NASA Glenn Research Center (GRC)
D. Spry / CO-I — GRC
M. Krasowski / CO-I — GRC
R. Herrick /Science PI — Univ. of Alaska/Fairbanks (UAF)
Michael West / CO-I — UAF
T. Pike / Collaborator — Imperial College of London

Technology Overview/Description

Overall objective: Leverage existing MEMS seismic sensor, recent developments in high-temperature electronics and sensors, terrestrial analogues and Venus seismicity studies, and an expert team to design and mature a MEMS based seismometer suitable for use on long-duration Venus landers, like SAEVe.

Accomplishing this involves:

- Assessing / modifying existing MEMS seismic sensors that may be suitable for Venus applications

- Developing driving/interfacing electronics to support required operations and interfaces of a notional lander

- Design and fabricate a 1-axis instrument (but readily scalable to 3 axis) and verify performance via tests and analysis. Iterate.

-Mature instrument and demonstrate performance of breadboard system in Venus surface conditions against model-based predictions and reach a TRL of 4 or greater

Technology Goals

1. Develop science-based requirements for a Venus seismometer that considers the Venus unique operations circumstances
2. Assess MEMS seismic sensors, modify as required, and fabricate and test under Venus conditions
3. Analyze the sensor / electronics system and design, fabricate and test a 1 axis system that meets requirements and is consistent with expected Venus mission applications
4. Demonstrate operations of breadboard 1 axis instrument in Venus conditions

Starting TRL: 2 **Ending TRL: 4**

Motivation: Venus Scientific Goals

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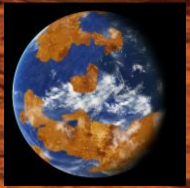
- Venus and Earth have several similarities
  - Almost same size, location in the solar system, mass
- However, in many ways they are very different
  - Atmosphere composition, temperature, H_2O, magnetic field, spin, etc…

Why?
How?



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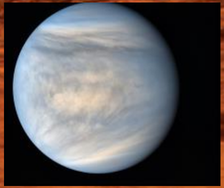
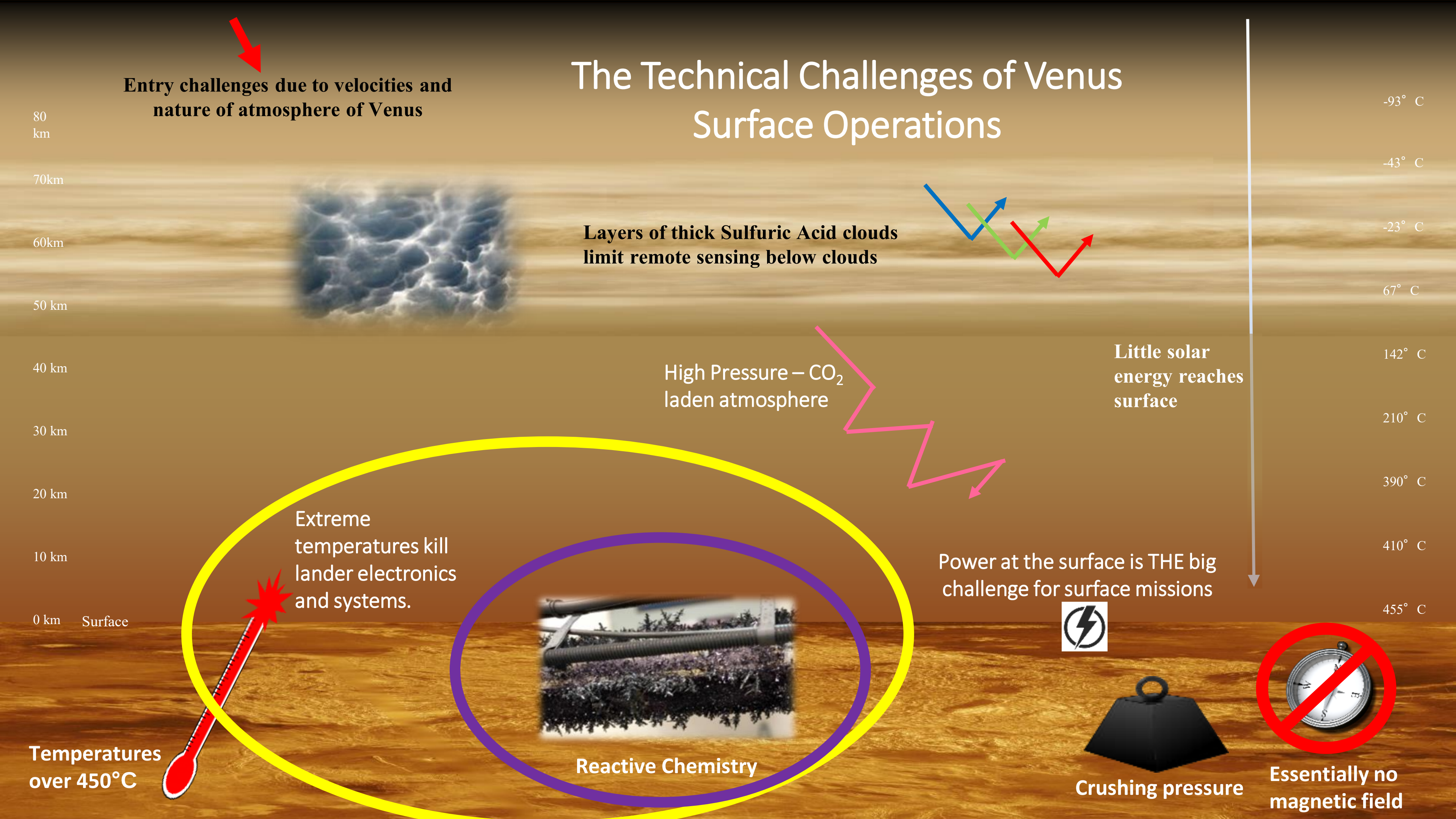


- Small surface landers like LLISSE, or the SAEVe lander concept, will help answer these and other other high-priority questions such as:
  - *How volcanically and tectonically active is Venus today?*
  - *What may we learn about exoplanets - from our backyard?*
  - *Why and when did the climates of Venus and Earth diverge?*

https://www.nasa.gov/feature/goddard/2016/nasa-climate-modeling-suggests-venus-may-have-been-habitable


The Technical Challenges of Venus Surface Operations
Entry challenges due to velocities and nature of atmosphere of Venus
80 km
70km
60km
50 km
40 km
30 km
20 km
10 km
0 km
Surface
Layers of thick Sulfuric Acid clouds limit remote sensing below clouds
High Pressure – CO_2 laden atmosphere
Little solar energy reaches surface
-93° C
-43° C
-23° C
67° C
142° C
210° C
390° C
410° C
455° C
Extreme temperatures kill lander electronics and systems.
Power at the surface is THE big challenge for surface missions
Temperatures over 450°C
Reactive Chemistry
Crushing pressure
Essentially no magnetic field

HOTTech-2 Seismometer Development Plan

National Aeronautics and Space Administration

Work has been broken down into four primary tasks:

- Task 1: Requirements development
- Task 2: Seismic Sensor Development
  - Using InSight for a baseline sensor, modify sensors as needed for the environment and to work with SiC electronics and the balance of a high temp instrument.
- Task 3: Instrument Development and Testing
  - Integrated testing will be done all the way to ensure compatible and system level success.
- Task 4: System Demonstration
  - High temperature testing of the sensor using a shaker table and analog silicon circuits will characterize responses to known inputs (vibration).
  - GEER testing of the sensor will demonstrate operation at expected environments.
  - Field testing in Alaska will demonstrate system response at expected quake levels while being directly compared to proven terrestrial sensors.
  - Integrated testing using SiC circuits and seismometer sensor in GEER will demonstrate system operability.

Driver Science Drivers & Constraints

- An important constraint for the design of a landed seismometer on Venus is a priori information on the recurrence rate (frequency) and size (magnitude) of expected events.
    - This is important given the limited expected duration of operation on the Venus surface of 60-120 days.
- Two independent approaches were explored to address the expected magnitude-frequency distribution of quakes on Venus.
    - Theoretical approach to estimating Venus seismicity
    - Scaling short duration terrestrial seismicity
- Operations not like typical terrestrial.
    - Limited lifetime, power, and data volume (e.g., reduced frequency range)
    - Little is known about wind / environmental noise

UAF Science Team Contributions To Instrument Design - Overview

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- Instrument Specifications – Required sensitivity, bandwidth, sample rate, etc.
  - With ability to transmit total of ~50 quakes in ~100 days, using pessimistic seismicity estimate need to be sensitive enough to see 1 quake every 2 days.
  - Lower seismicity estimate -> need to record smaller quakes -> more high-frequency content required -> higher sample rate to keep data interpretable.
  - Combining theoretical approaches and empirical approaches.
- Primary expected noise source – wind
  - Environmental noise must be made less than smallest quake we wish to record.
  - All indicators are that bottom of Venus atmosphere is stable with low wind speeds (< 1 m/s), but high density of atmosphere at surface means outsized effect.
  - Seismometer on Venus surface bracketed by conditions of terrestrial surface and ocean bottom. Comparing sub ocean surface quake data to surface data can provide insights on effects of noise, mitigation, and coupling (unlike most on-land seismometers, off-shore stations are not buried and are just dropped to surface).

Theoretical Estimations of Seismicity on Venus

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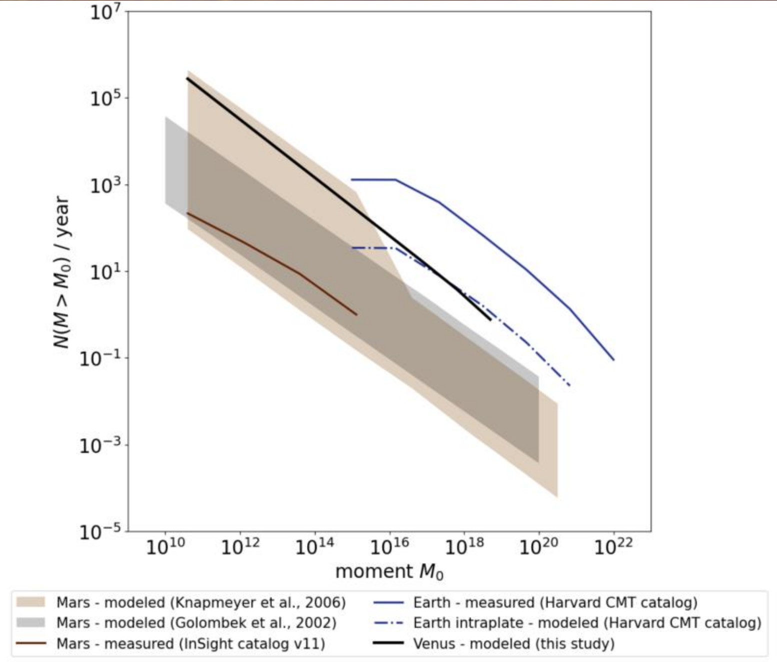
Stresses in the Earth's lithosphere that are not associated with plate boundaries include contraction of the lithosphere (global), and mantle plumes (regional).

We focus on global seismicity here and compute cumulative seismic moment arising from lithospheric contraction.



FINDINGS

Predicted seismicity for Venus is

- similar to the seismicity of intraplate regions on Earth,
- higher than the regional seismicity measured by InSight, and
- towards the upper limits of predicted seismicity in Mars

Next step – for theoretical approaches, global seismicity needs to be translated to what is recorded at some generic station based on amplitude reduction with distance from quake.

Scaling Short Duration Terrestrial Seismicity

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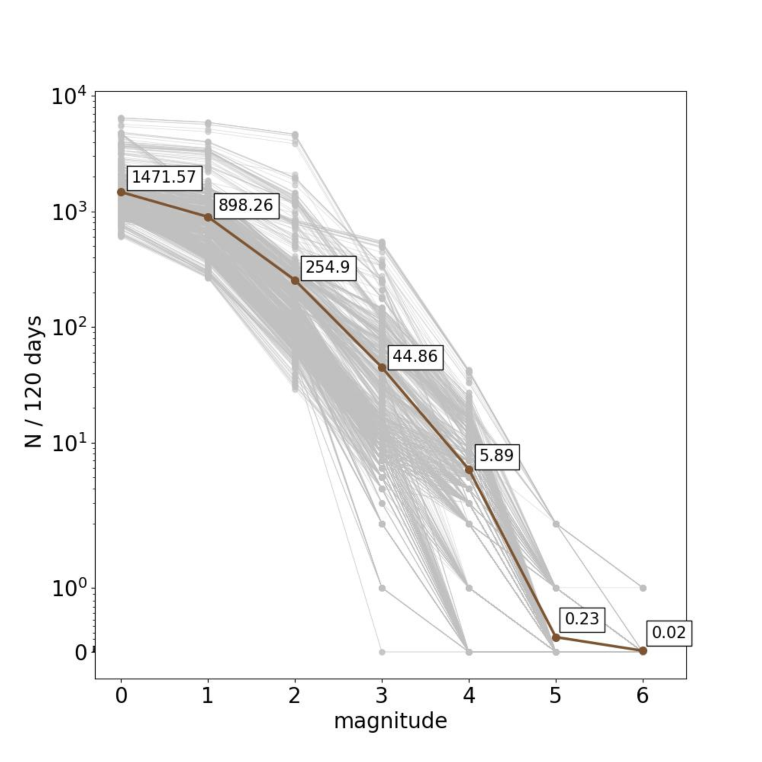
We treat Earth as an analog and compute short duration magnitude frequency distribution of quakes by:

- Compiling 1000 seismic catalogs, each containing events from randomly selected 120-day periods between 2000-2021, by querying the USGS database.
- Excluding all events that either have magnitudes > 7 or are occurring at depths > 50 km to exclude deep subduction related events expected to be unlikely on Venus.



FINDINGS

- More conservative estimate compared to theoretical approach.
- Only ~ 5-6 events of magnitude > 4 might be detected within 120 days.

How The Same Quake Looks At Different Depths

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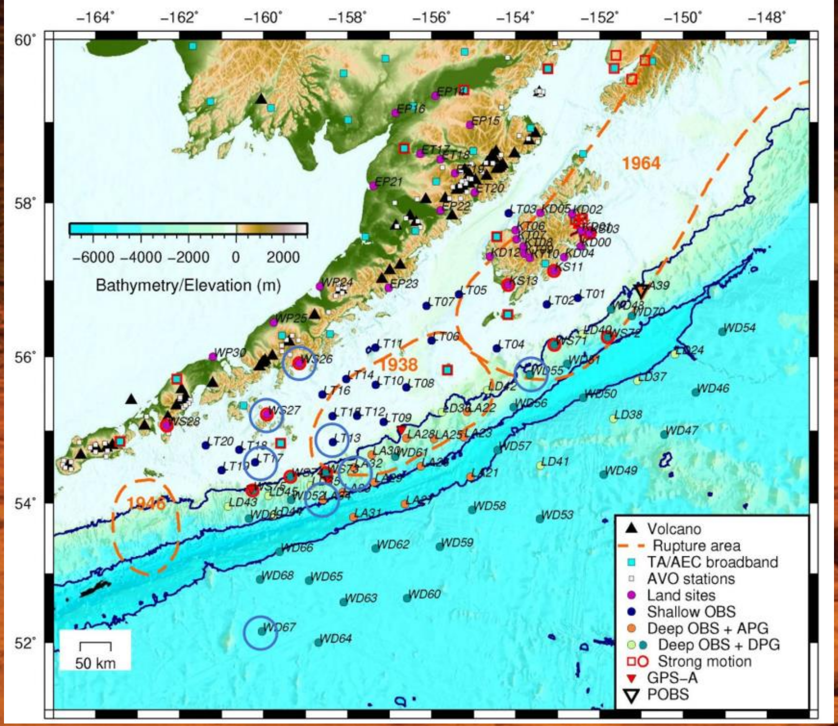
Alaska Amphibious Community Experiment (AACSE)

- A shoreline-crossing, passive/active seismic experiment executed from May 2018 through August 2019 in the Aleutian subduction zone spanning Kodiak Island and the Alaska Peninsula.
- A total of 105 broadband seismometers: 30 on-land and 75 in Ocean Bottom Seismometer (OBS) packages.

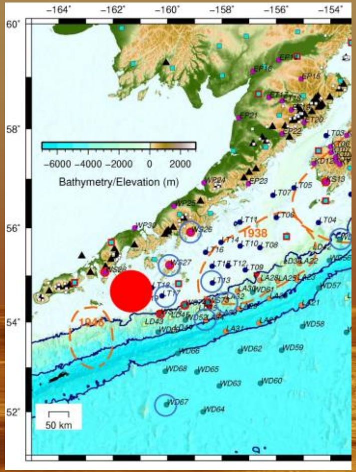
For atmosphere-ground interaction on Venus

- Signal analysis of OBSs: on-land, shallow (100 – 200m), medium (1200 – 1600m), deep (> 4600m).
- Between 7/1/2018 and 6/30/2019, there were 216 earthquakes (magnitude ≥ 3) in the region limited by longitude of -151 – -162 and latitude of 54 – 60.
  - Magnitude ≥ 6:1
  - 5 ≤ Magnitude < 6:10
  - 4 ≤ Magnitude < 5:28

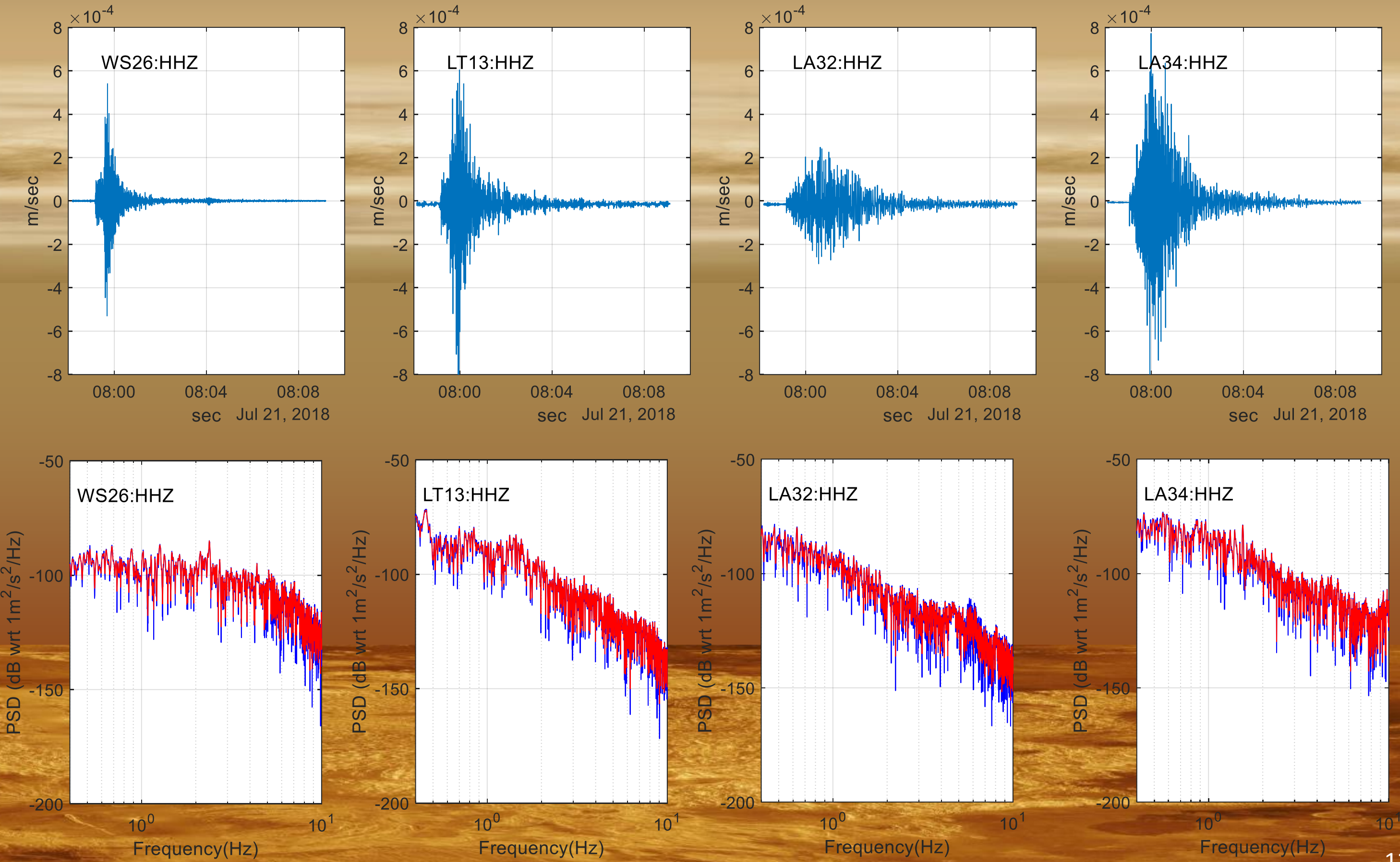


7/21/2018 earthquake

- Ml = 5.2
- Lat: 54.4758
  Long: -160.8295
  Depth: 32.69km



On-land	Shallow 100 – 200 m	Medium 1200 – 1600 m	Deep > 4600 m



Preliminary Risks

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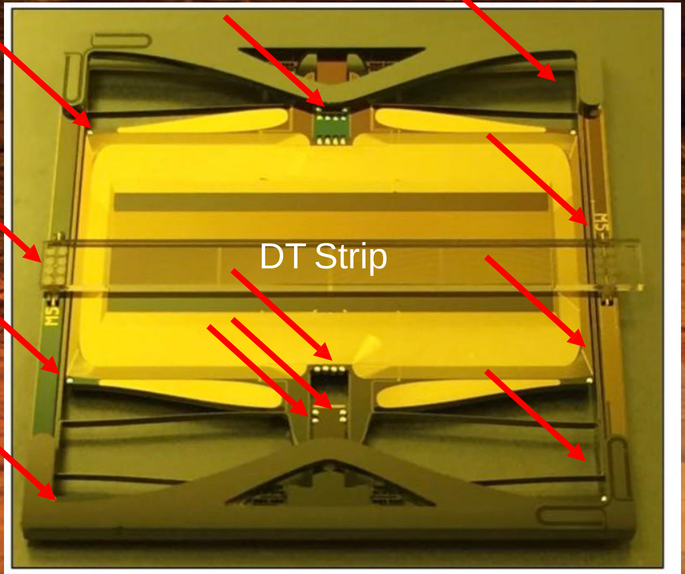
- The aim of this work is to identify the critical aspects that might lead to the failure of this sensor in a Venus environment
- Solder used to bond DT strip to sensor die will fail at Venus temperatures
- Solder used for shock protection on sensor die will fail at Venus temperatures
- Therefore this work concentrated on possible failures



Imperial College London

Bonded Strip Sensors

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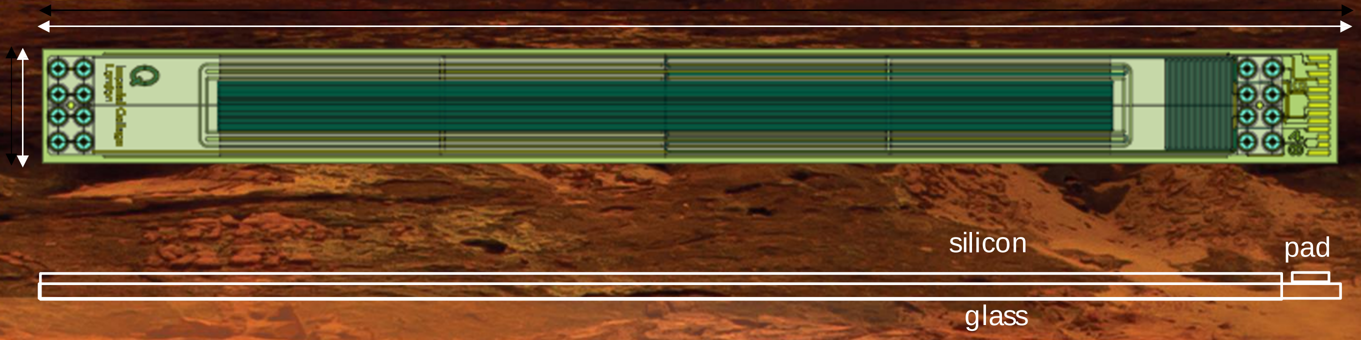

- These incorporate a 50 Hz Si suspension die and a DT strip.
- Allows measurement of capacitance.

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Instrument Development – Technical Plan

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- Assess MEMS insight seismometer for potential Venus application, modify as needed.
- Develop and trace engineering requirements to science.
- Develop circuit designs based on viable high-temperature electronics that will drive sensors, process data, and output to future hosting lander.
- Develop unique electronic components, if needed to enable project objectives, however, most devices are already in development by other efforts.
- Develop instrument design for a 1 axis seismometer (readily scalable to 3) such that overall noise in the system is lower than the expected signals to be measured.
- Test along the way but conclude with demonstration of system at conditions and required performance levels.

Technical Challenges / Constraints

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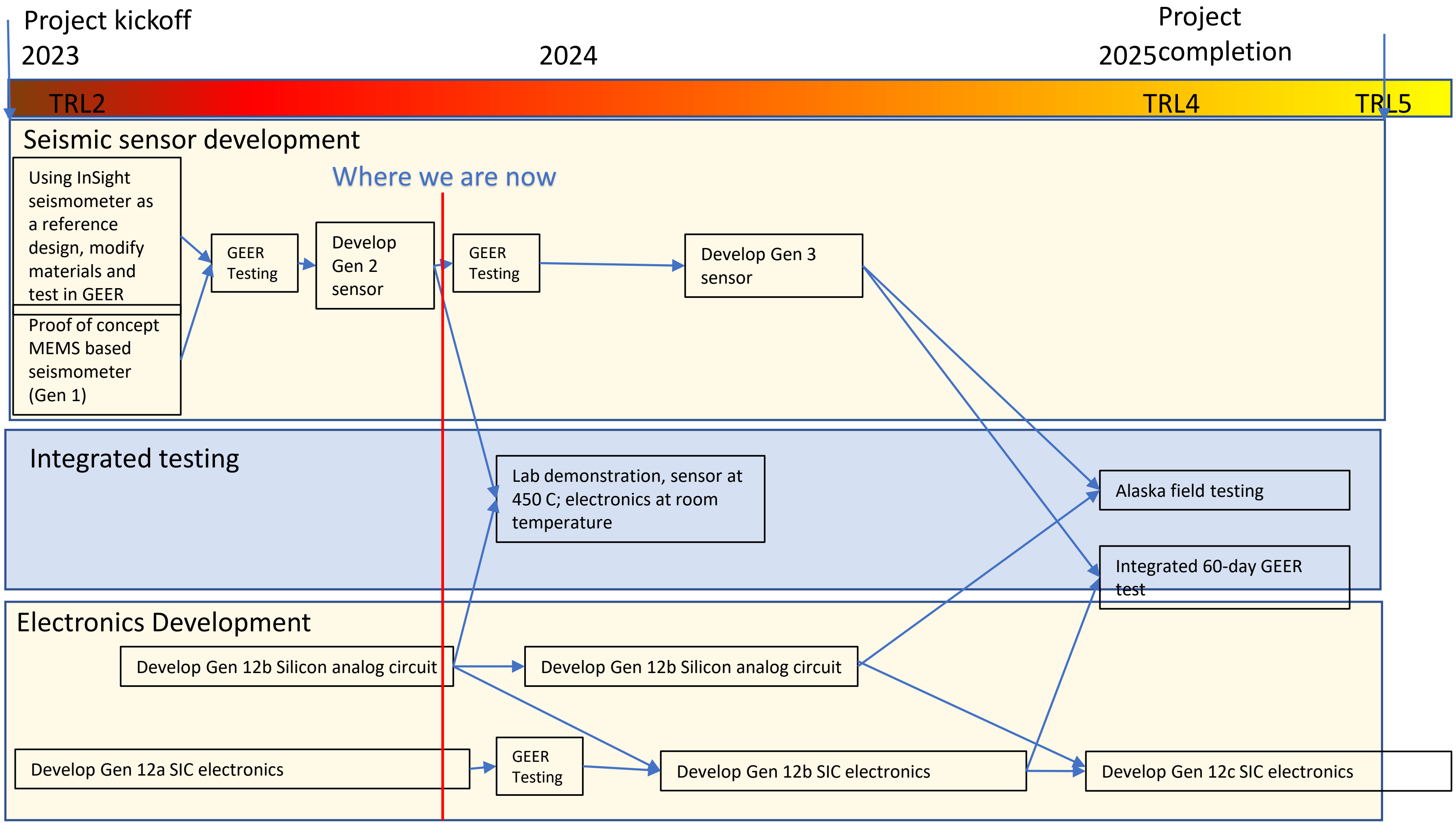
- Limited power (only ~ 50 events can be transmitted [eliminate wind noise and less insightful events]).
- Limited data to inform expectations of local seismic and environmental noise conditions.
- Components and instrument to operate at 460°C, 92 bar, reactive and dense atmosphere.
- SiC devices are not as complex and more power hungry that conventional electronics.
  - Only simpler and slower processing possible
- Data volume likely constrained to hundreds of bits / second.



Project kickoff
2023
2024
Project
2025
completion
TRL2
TRL4
TRL5
Seismic sensor development
Where we are now
Using InSight seismometer as a reference design, modify materials and test in GEER
Proof of concept MEMS based seismometer (Gen 1)
GEER Testing
Develop Gen 2 sensor
GEER Testing
Develop Gen 3 sensor
Integrated testing
Lab demonstration, sensor at 450 C; electronics at room temperature
Alaska field testing
Integrated 60-day GEER test
Electronics Development
Develop Gen 12b Silicon analog circuit
Develop Gen 12b Silicon analog circuit
Develop Gen 12a SIC electronics
GEER Testing
Develop Gen 12b SIC electronics
Develop Gen 12c SIC electronics

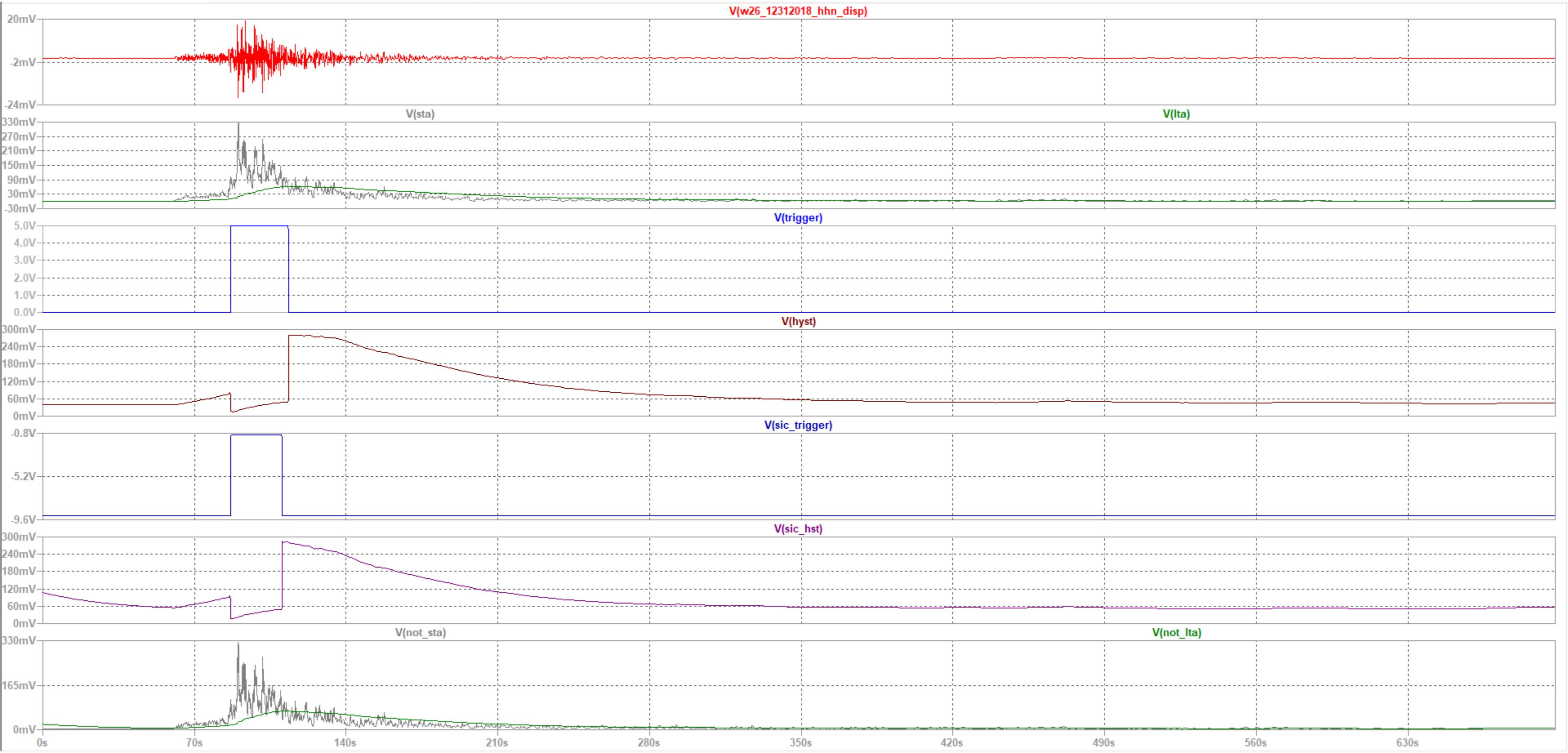
Components Team Progress

- Defined device objectives and assess relative to performance needs and application constraints.
- Working device fabrication requirements into sequence of hardware development and test flows.
- Fabricating devices as possible through process flows.
- Supporting balance of team.

Circuits Team Progress

- Assessed design and interface requirements for expected Sensor.
- Developed circuits to drive and interrogate said sensor in light of science requirements and engineering / system constraints.
- Modelled current and expected SiC devices and developed circuit simulations to achieve performance objectives and explore trades relative to constraints and science objectives.
- This includes various triggering approaches, data processing, power reduction approaches, and more.
- Example:

Simulated the analog trigger mechanism in silicon and in silicon carbide using actual quake data. Results between the two were virtually identical. (w26_12312018_hhn_disp example below)



Project / Team

- Great team in place and tertiary support identified as needed.
- Regular team meetings (bi-weekly), F-2-F annually
- Project support.
  - Requirements development / tracking (review in next couple months)
  - Schedule refinement and tracking
  - More rigorous risk and mitigation tracking coming
- Leveraging other activities as possible.
  - SiC fab runs
  - Investigation and activities on other programs that can help us
    - e.g., EPSCoR

Collaborating

- Areas where technology advancements would enhance or enable more science.
  - More complex and lower power high-temperature electronics
  - High-temperature / low power memory
  - Longer lasting power systems
  - User update capability over mission life (e.g., High-temperature receiver technology)
    - E.g. Adjustment of trigger parameters over mission duration
  - Deployment consistent with very small, low complexity lander platform
- Others
- Year 3 test – demonstration
  - Looking at results of memory - highly enhancing
  - Possible simple deployment
  - Complementing sensors/ instruments for Venus science

Questions?